AARTFAAC: Towards a 24x7, All-sky Monitor for LOFAR

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The AARTFAAC project aims to implement an All-Sky Monitor (ASM) using the Low Frequency Array (LOFAR) telescope. It will enable real-time, 24x7 monitoring for low frequency radio transients over most of the sky locally visible to the LOFAR at timescales ranging from seconds to several days, and rapid triggering of follow-up observations with the full LOFAR on detection of potential transient candidates. These requirements pose several implementation challenges: imaging of an all-sky field of view, low latencies of processing, continuous availability and autonomous operation of the ASM. The first of these has already resulted in the correlator for the ASM being the largest in the world in terms of the number of input data streams. We have carried out test observations using existing LOFAR infrastructure, in order to quantify and constrain crucial instrumental design criteria for the ASM. In this paper, we present an overview of the AARTFAAC data processing pipeline and illustrate some of the aforementioned challenges by showing all-sky images obtained from one of the test observations. These results provide quantitative estimates of the capabilities of the instrument.

Key words: Calibration, Imaging, Aperture Array, Radio Sky Monitor, Radio Transients.

1. Introduction

The recent serendipitous discoveries of several astrophysical radio transients at a variety of flux and time scales (see e.g. [1]) have opened up a new window in the search for exotic objects of both known and unknown type. It is felt that the transient or dynamic radio sky, especially at low frequencies, will be rich enough to benefit from blind surveys along the lines of wide field instruments at higher energies (X and γ rays), which have been very successful at detecting transient sources. At low radio frequencies, a possible population of rare, but bright transients has been revealed, although only serendipitously. Due to their rarity, detection of such sources can benefit from continuous sky monitoring with instruments having as wide a field of view as possible, even while trading off sensitivity.

In this context, the Amsterdam-ASTRON Radio Transient Facility And Analysis Center (AARTFAAC) (a collaboration between ASTRON, The University of Amsterdam, and the Oxford e-Research Center) aims to implement a near real-time, 24x7 All-Sky Monitor (ASM) for the LOFAR[2]. Such an instrument will enable detection and monitoring of low frequency radio transients

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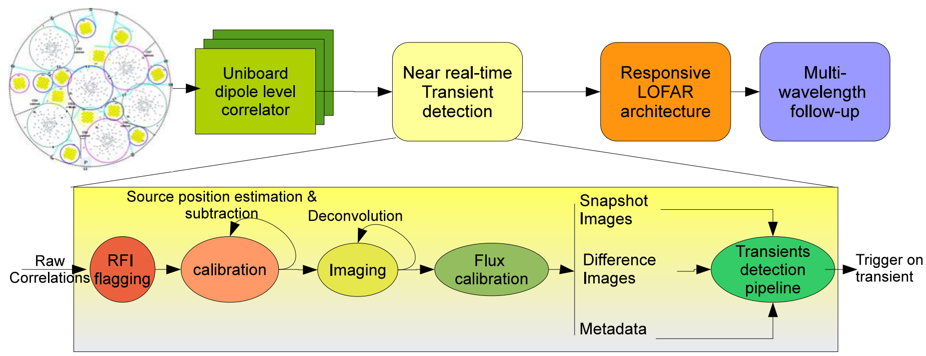

Figure 1. The main components of the AARTFAAC ASM.

over most of the sky locally visible to the LOFAR, at timescales ranging from seconds to several days. In the following sections, we introduce the ASM in more detail and present some initial results.

2. The AARTFAAC ASM

Each station of the LOFAR array is itself a sub-array composed of two kinds of receiving elements: dipoles or Low Band Antennas (LBA) operating between 10-80 MHz, and phased array tiles of 4x4 High Band Antennas (HBA), operating between 110-240 MHz. The ASM will use six stations at the heart of LOFAR and will be a zenith-pointing, transit mode instrument. This configuration makes the ASM a 288-element dual, or 576-element single polarized array spread over ∼350 m, thus providing almost full UV coverage with a well defined PSF which does not change with time. The ASM requires correlation between signals from all paths in order to image the full element field of view (2π sr, or entire local celestial hemisphere for LBA and ∼1.5%-10% of the sky for the HBA, depending on the observing frequency). To enable continuous monitoring, the ASM will operate in a piggyback fashion simultaneously with regularly scheduled observations, sharing their observational parameters. The overall control flow and main components of the ASM are depicted in Fig. 1. The AARTFAAC correlator will have 576 inputs, requiring the estimation of $\sim 1.65\text{x}10^5$ correlations for each spectral channel. In its implementation [3], correlation is distributed on station based hardware (built on the Uniboard project), with a 24 kHz spectral and 1 second temporal resolution (to prevent time and bandwidth smearing). The 60 MHz resolution of 0.8^o leads to a confusion noise of ∼8 Jy, while the 0.4^o resolution at 160 MHz leads to a confusion noise of ∼1 Jy. The ASM subband images (∼200 kHz, thermal noise of ∼8 Jy@60 MHz, ∼0.6 Jy@160MHz) are hence expected to be confusion noise, rather than thermal noise limited. The total available bandwidth is ∼13 MHz, which can be arbitrarily selected from the 100 MHz total digitized band. Thus, the ASM has a very versatile instantaneous spectral coverage over two octaves in the LBA, and one octave in HBA.

The first stage RFI excision is challenging because of the limited temporal and spectral baseline available, due to the near real-time nature of the system. The compute intensive calibration and imaging can require multiple iterations, but should still have a low latency. After flux calibration, the images will be fed through the Transients Pipeline [4]. This carries out source extraction and association, and the generation of light curves from existing observations for transient detection. It will also generate low-latency triggers to a LOFAR architectural module termed the 'Responsive LOFAR module', which can trigger multi-wavelength follow-up observations with a variety of instruments.

3. ASM Calibration Challenges

Calibration refers to the estimation of a complex direction independent gain per antenna and direction dependent parameters per calibration source, characterizing the ASM and propagation through the ionosphere. Traditionally, calibration is carried out periodically, with the expectation that instrumental and observational parameters remain stable in the interim. However, the ionosphere can have a significant effect on the propagation of low frequency radio waves as observed by the ASM, requiring continuous, direction dependent calibration of each timeslice. We use a Weighted Alternating Least Squares algorithm for multi-source self-calibration, as described in [5]. The algorithm solves for the best fitting calibration solutions in a Least-Squares sense and requires an initial sky model.

Transient detection is proposed either via analysis of each source's light curve, generated by source extraction on every image timeslice, or via image level differencing. Both techniques require the minimization of calibration errors to reduce the false detection rate of transients. However, one of the contributors to calibration errors are shifts in the observed positions of the sources in the sky-model due to ionospheric refraction, leading to model visibilities differing from observed visibilities, and hence, non-convergence of calibration. We address this by estimating source positions from data using Weighted Subspace Fitting (WSF) [6], incorporated into every calibration cycle. The dynamic range of calibrated images is then improved by the subtraction of the visibility contribution of the brightest sources in the sky, along with their sidelobes. Further, the ASM in LBA mode just resolves the Sun. This precludes its modeling as a point source, while also preventing the suppression of the Solar flux by eliminating short baselines. During solar activity, e.g. flares, the Sun can be the dominant contributor of flux to visibilities, while morphing into a source containing multiple complicated components which change with time. We have applied a sparse-reconstruction based algorithm to estimate a reasonable model of the flaring Sun in an automated manner. This was found to be effective, although compute intensive. Thus, the approaches described above allowed for effective removal of the Sun and the bright radio sources dominating the observed visibilities. For algorithm validation while hardware is being developed, test data from all dipoles of six stations were acquired using existing LOFAR hardware and software. Fig. 2 shows images from data acquired on September 21, 2011, 12:39 hours UTC before and after the removal of the Sun and bright sources. This image at 60 MHz (10 s integration, 90 kHz bandwidth) has a dynamic range of $\sim 2200:1$. The estimated noise is ~ 10 Jy, close to the theoretical value of 4Jy.

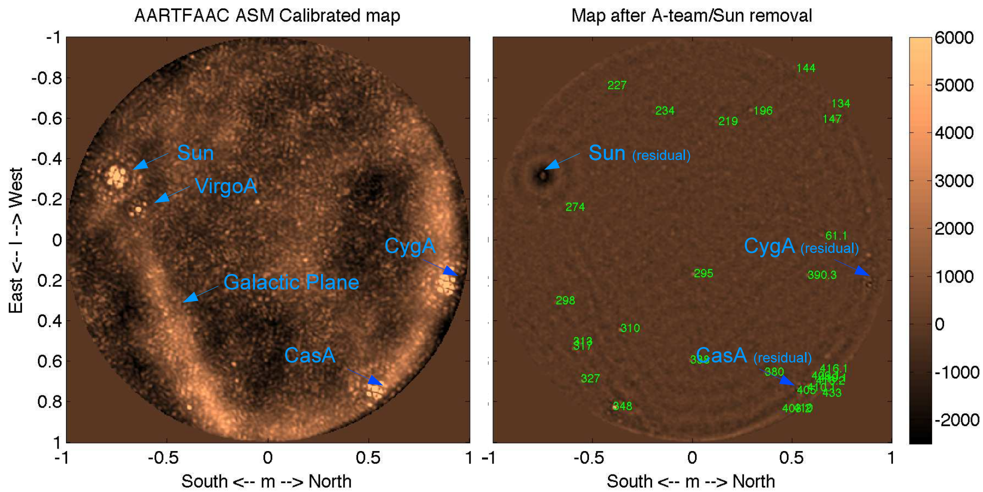

Figure 2. :All-Sky zenith tangent projection maps in local coordinates, intensity in arbitrary units. (Left) Phase and gain calibrated map with flaring Sun, CasA, CygA and Galactic plane visible, (Right) Subtracting the Sun and bright sources, and filtering the Galactic plane from the left map reveals (labelled) weaker sources. Maps created at 60 MHz, $\Delta\nu \sim 90$ kHz,$\Delta t \sim 10$s.

4. Conclusion

The AARTFAAC ASM will be one of the first all-sky monitors at radio wavelengths. Its calibration is challenging because of the dynamic nature of the low frequency observations due to factors like an active ionosphere over an extremely large field of view, or Solar activity. We have shown that advanced algorithms can effectively address some factors at the cost of increased computing. The ASM's implementation is ongoing, with appropriate hardware procured and firmware in development. Appropriate calibration approaches are being developed based on experience gained via test observations.

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